Environmental Science & Technology

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Long-Term and Seasonal Trend Decomposition of Maumee River Nutrient Inputs to Western Lake Erie

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Supporting Information

ABSTRACT: Cyanobacterial blooms in western Lake Erie have recently garnered widespread attention. Current evidence indicates that a major source of the nutrients that fuel these blooms is the Maumee River. We applied a seasonal trend decomposition technique to examine long-term and seasonal changes in Maumee River discharge and nutrient concentrations and loads. Our results indicate similar long-term increases in both regional precipitation and Maumee River discharge (1975−2013), although changes in the seasonal cycles are less pronounced. Total and dissolved phosphorus concentrations declined from the 1970s into the 1990s; since then, total phosphorus concentrations have been relatively stable, while dissolved phosphorus concentrations have increased. However, both total and dissolved phosphorus loads have increased since the 1990s because of the Maumee River discharge increases. Total nitrogen and nitrate concentrations and loads exhibited patterns that were almost the reverse of those of phosphorus, with increases into the 1990s and decreases since then. Seasonal changes in concentrations and loads were also apparent with increases since approximately 1990 in March phosphorus concentrations and loads. These documented changes in phosphorus, nitrogen, and suspended solids likely reflect changing land-use practices. Knowledge of these patterns should facilitate efforts to better manage ongoing eutrophication problems in western Lake Erie.

INTRODUCTION

Eutrophication problems resulting from excessive nutrient inputs have plagued Lake Erie for many years. In 1965, an article in *The Economist* declared that Lake Erie was "literally dying".[1] To control eutrophication, the 1978 Great Lakes Water Quality Agreement (GLWQA) established target total phosphorus (TP) loads for each of the Great Lakes, including an 11 000 metric tons per year goal for Lake Erie.[2] Following implementation of the 1978 Agreement, notable phosphorus reductions and corresponding water quality improvements were documented.[3] However, the Lake Erie phosphorus target is still occasionally exceeded,[4,5] and since the mid-late 1990s, symptoms of "re-eutrophication", including increased phytoplankton biomass and a reappearance of widespread hypoxia, have been documented.[6,7] In 2011, despite meeting the TP load target, Lake Erie experienced the most extensive algal bloom on record.[8] In August 2014, the city of Toledo drinking water supply was temporally shut down because of high toxin levels resulting from a *Microcystis* bloom.

The resurgence of eutrophication in Lake Erie has prompted the National Oceanic and Atmospheric Administration (NOAA) and partners to develop predictive models for harmful algal bloom (HAB) occurrence[9−11] and issue regular bulletins for potentially affected stakeholders (http://www.glerl.noaa.gov/res/waterQuality/). Additionally, the updated 2012 GLWQA mandated a review of the existing TP target loads with a directive to update the Lake Erie target and develop numerical phosphorus concentration criteria within 3 years.[12]

Lake Erie's most severe algal blooms originate in the western basin of the lake, where nutrient inputs from the Maumee River (Figure 1) drive algal growth.[6,13] Unlike many Great Lakes tributaries where input data are sparse, making long-term estimation and inference uncertain,[14] nearly continuous records of approximately daily concentration data are available for phosphorus, nitrogen, and other constituents in the Maumee River. These data are collected by Heidelberg University and in combination with available United States Geological Survey (USGS) discharge monitoring records allow for detailed analyses of changes in nutrient loads and concentrations since the late 1970s. Previous examination of long-term patterns in

Received: December 23, 2014
Revised: February 13, 2015
Accepted: February 13, 2015
Published: February 13, 2015

DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392−3400

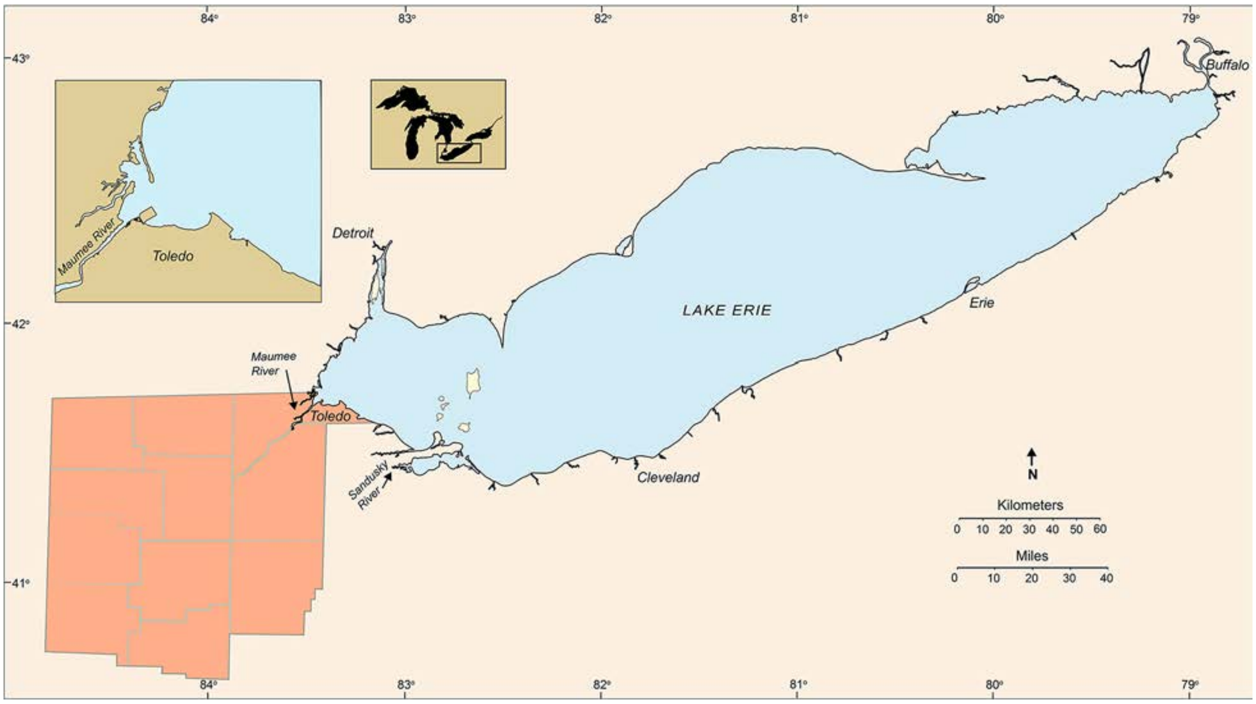

Figure 1. Lake Erie map. The upper right inset depicts all five Laurentian Great Lakes with Lake Erie enclosed in a rectangle. The upper left inset shows the mouth of the Maumee River in the western Lake Erie basin. The orange area indicates Ohio region 1, the area represented by the precipitation data.

the annual phosphorus loads and flow-weighted mean concentrations from the Maumee River revealed substantial increases in bioavailable phosphorus forms since the early 1990s, while TP changed little or decreased slightly.[13]

In this analysis, we build on previous work[13] and use an approach to simultaneously examine both long-term and seasonal fluctuations in nutrient concentrations, loads, Maumee River discharge, and regional precipitation. Environmental trend analyses commonly employ linear regression or non-parametric methods based on order statistics, including Kendall's tau test[15] and variations.[16,17] However, these methods are most appropriate for linear or monotonic trends; assessments using them may be inaccurate when the supporting assumptions are not well met or when the data fluctuate with time. Polynomial regression is sometimes applied for nonlinear time-series analysis, but this approach uses the entire time range of observations to estimate nonlinear patterns, whereas non-linearities are often temporally local features. Generalized additive modeling[18] is a graphical approach to highlight nonlinear patterns in data based on various localized smoothing techniques (also known as smoothers). To highlight seasonal and long-term patterns in Maumee River data, we apply a form of generalized additive modeling: seasonal trend decomposition using loess (STL),[19,20] which employs a locally weighted running-line smoother and has been previously used to analyze long-term nutrient concentration and river discharge data.[21,22] Our results suggest that long-term precipitation increases are partially responsible for discharge and load increases since the mid-1990s and that the seasonal timing of delivery has also changed for some constituents.

■ METHODS

Water quality data were downloaded from the National Center for Water Quality Research website (http://www.heidelberg.edu/academiclife/distinctive/ncwqr/data). Data from the Maumee River were collected at the Bowling Green Water Treatment Plant, which is located 5.6 km upstream from the USGS stream gage in Waterville, OH (USGS 04193500). Samples were collected using an ISCO automated sampler that pulled water from a receiving basin continuously flushed with river water via a submersible pump in the river. Discrete samples were collected either 3 (1974−1988) or 4 (1988−present) times a day, and all samples collected during high flow or with high turbidity were analyzed. Otherwise, one sample per day was analyzed. Samples were retrieved weekly and returned to the laboratory for analysis following standard United States Environmental Protection Agency (U.S. EPA) protocols. Dissolved reactive P (DRP) and TP were both analyzed using molybdate blue colorimetry (U.S. EPA Method 365.3); TP was pretreated using persulfate digestion. Nitrate (NO_3^-) was analyzed using ion chromatography (U.S. EPA Method 300.1). Total Kjeldahl N (TKN) was analyzed using phenol colorimetry after pretreatment with acid digestion (U.S. EPA Method 351.2). Total N was calculated as the sum of NO_3^- and TKN. Finally, total suspended solids (TSS) was analyzed by measuring dry weight after filtration through a glass fiber filter (U.S. EPA Method 160.2).

We downloaded average monthly precipitation data for Ohio region 1 from the NOAA National Climatic Data Center, Midwest Regional Climate Center website (http://mrcc.isws.illinois.edu/CLIMATE/index.jsp.).

Before analyzing the data, we first averaged the Maumee River concentration data by day (when multiple measurements were available) and then averaged the daily data by month to obtain monthly average concentrations. We estimated loads first on a daily basis by multiplying the average daily concentration by average daily discharge from the USGS stream gage (USGS 04193500) and then on a monthly basis by

DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392−3400

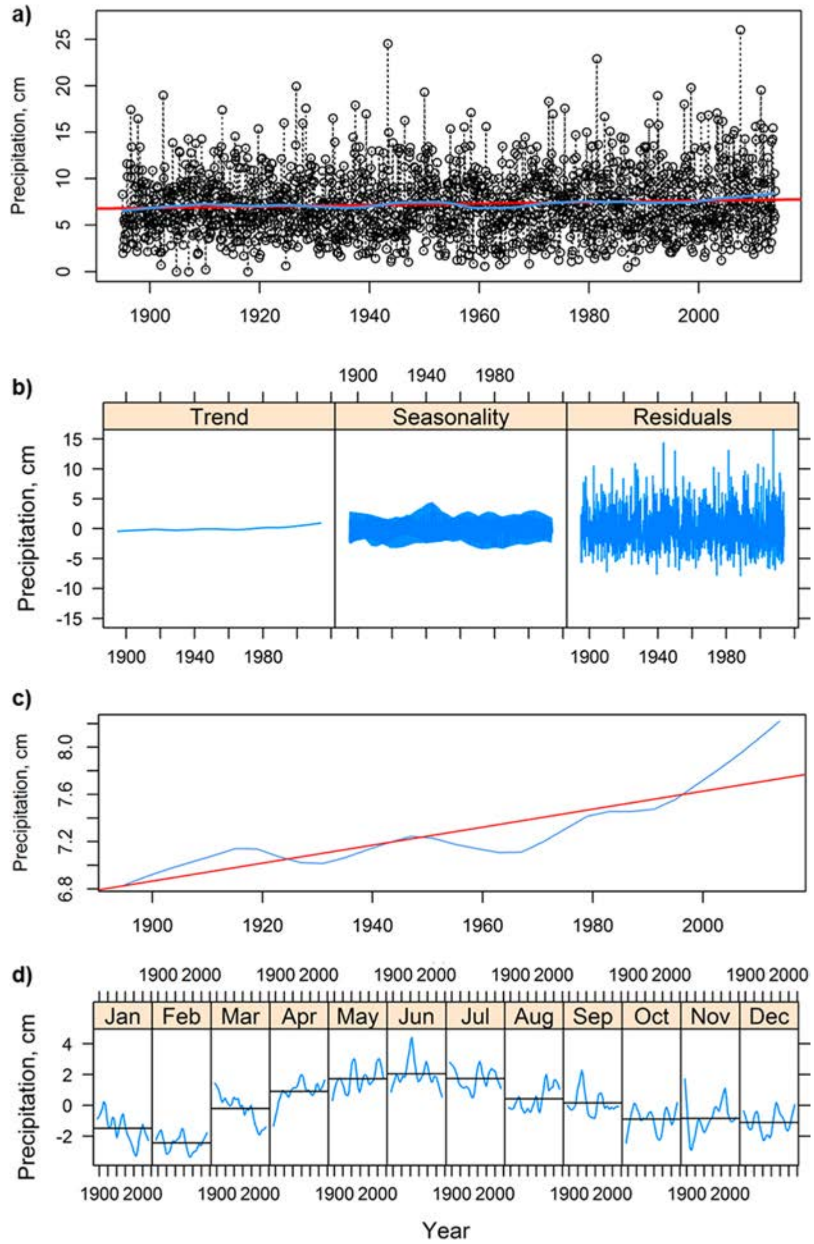

Figure 2. (a) Ohio climate region 1 monthly average precipitation data (1895−2013) with STL long-term trend line (blue) and least-squares line (red). (b) STL long-term trend centered at zero (left), seasonal pattern (middle), and residuals (right). Seasonal pattern and residuals are shown as deviations from the long-term trend. (c) Enhanced resolution depiction of STL long-term trend (blue) and least-squares line (red). (d) STL seasonal patterns depicted by month (blue curves) with corresponding long-term monthly averages (black horizontal lines), shown as deviations from the smoothed, long-term trend.

summing the estimated daily loads. We then used the STL procedure on the average monthly concentrations and total monthly loads. Missing values early in the time series were imputed using long-term monthly means (see Figure S1 of the Supporting Information).

STL applies repeated loess fitting[23] to decompose monthly time-series data into smoothed trend, seasonal, and residual components. STL uses 1 continuous loess line for the smoothed, long-term component and 12 month-specific loess lines for the seasonal component. Fitting is performed on each component iteratively until the resulting trend and seasonal components no longer differ from those of the previous iterations. There are two smoothing parameters in the model, representing the window widths of the seasonal and long-term components. We chose window widths of 48 and 250 months, respectively, to visually reveal trends. Generally, window widths are selected to produce relatively smooth long-term patterns that highlight potentially important underlying changes while simultaneously reducing the residuals to white noise. Attaining both of these goals is a balancing act; sometimes the residuals reveal noteworthy signals.[24] However, in this analysis, no signals were evident in the residuals; thus, our results focus on the smooth long-term and seasonal patterns.

RESULTS

To illustrate the STL approach, we first applied it to the entire available period (1895−2013) of monthly average precipitation data (Figure 2). Over this time span, the monthly data

DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392−3400

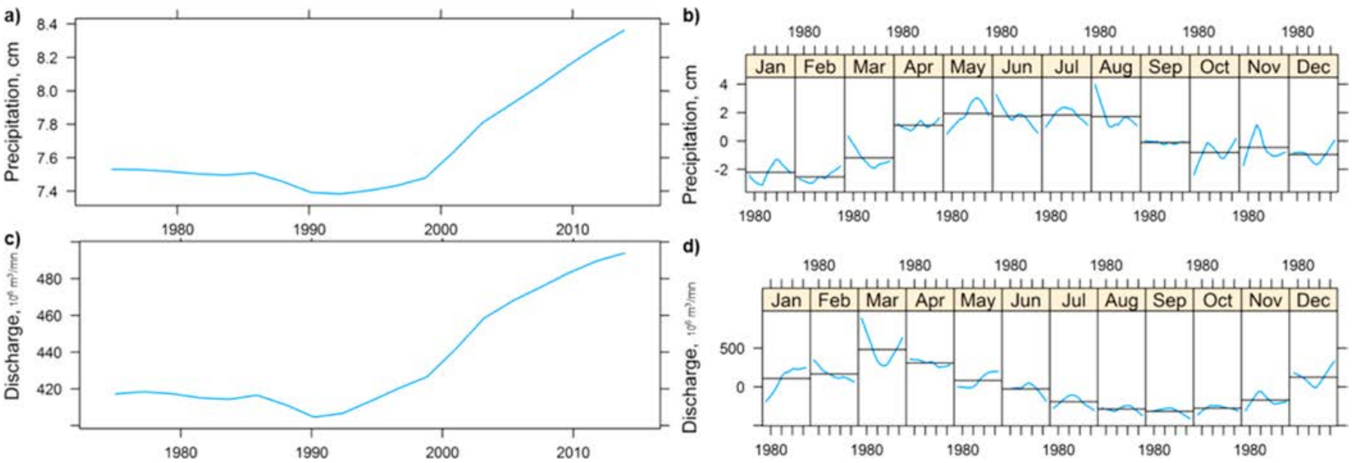

Figure 3. Panels a and b show enhanced temporal resolution (1975−2013) depiction of Ohio climate region 1 monthly average precipitation STL results for comparison to Maumee River discharge STL results over the same period. Panel a shows the STL long-term trend line, and panel b shows STL seasonal patterns by month as deviations from the smoothed, long-term trend (blue curves), with corresponding long-term monthly averages (black horizontal lines). Panels c and d show analogous Maumee River average monthly discharge STL results for the same period of record.

appeared noisy with no obvious visual pattern (Figure 2a). The STL procedure breaks the time series into three components: a long-term, smoothed trend (left panel in Figure 2b), a seasonal pattern that changes with time (middle panel in Figure 2b), and residuals (right panel in Figure 2b).

On the scale of the original monthly variability, the long-term, smoothed pattern was almost linear with no obvious trend (left panel in Figure 2b). Superimposed over the original monthly time series, the long-term, smoothed pattern went approximately through the middle of the observations and captured the subtle fluctuations in the data (Figure 2a). When resolution on the vertical scale was expanded, an overall increasing pattern was apparent, which deviated from a least-squares linear fit through the data (Figure 2c). Through the 1900s, a periodicity of approximately 30 years was distinguishable, similar in timing to a corresponding cycle previously reported in Great Lakes water levels.[24] A comparison with the least-squares line emphasizes an uptick in precipitation beginning in the early 1990s.

A view of the seasonal periodicity over the entire period of record was not of sufficient resolution to highlight clear patterns; however, this depiction did indicate that amplitude fluctuations in the cycle have occurred over this time (middle panel in Figure 2b). When the resolution was increased and seasonal patterns were depicted by month, several changes became more apparent (Figure 2d). The overall seasonal pattern displayed a minimum in February and a peak in June, and most months display only slight trends or apparent random fluctuations about the overall monthly average. January and March are exceptions, with both months showing a decrease over the period of record.

When we focus on data from 1975 to 2013, the period for which nutrients and sediment measurements are available for the Maumee River, the long-term, smoothed patterns for precipitation and Maumee River discharge were similar. Both precipitation and discharge were relatively stable from approximately 1975 to the late 1980s, declined slightly into the early 1990s, and steadily increased since the early to mid-1990s, with overall increases of approximately 12−16% (panels a and c of Figure 3). In contrast, the seasonal patterns for precipitation and discharge differed (panels b and d of Figure 3). The highest precipitation was from April to August, with minimum precipitation from January to February, whereas maximum discharge was in March, with minimum discharge from August to October (panels b and d of Figure 3). Changes in the seasonal pattern over time were not pronounced, except in March, where precipitation and discharge have increased since about 1990, a time approximately coincident with the increase in the long-term, smoothed precipitation and flow (panels a and c of Figure 3).

Long-term, smoothed TP concentrations declined steadily from 1975 until the late 1990s and, since that time, have been relatively stable or slightly increasing (Figure 4a). The long-term, smoothed TP load declined similarly to TP concentrations through the late 1990s but has risen steadily since approximately 2000, reflecting the concurrent increase in discharge, and is currently at levels comparable to those of the mid-1970s (Figure 4b). Long-term, smoothed dissolved reactive phosphorus (DRP) concentrations also declined from 1975 until approximately the early 1990s but have increased since then (Figure 4c). The long-term, smoothed DRP load decline from 1975 until approximately 1990 tracked that of the DRP concentration, but since approximately 1990, DRP loads have increased more rapidly than concentrations, with current levels slightly exceeding those of 1975 (Figure 4d).

Long-term, smoothed Maumee River nitrogen trajectories were almost the reverse of the phosphorus trends, with increases from 1975 until the early to mid-1990s and declines since that time (panels e−h of Figure 4). Long-term, smoothed total nitrogen (TN) concentrations increased from 1975 until the early 1990s and have decreased steadily since then (Figure 4d), while the long-term, smoothed TN load increased and remained fairly stable until the early 2000s but has decreased slightly since then (Figure 4f). Long-term, smoothed nitrate concentration and load patterns over time were similar to those of TN, because nitrate is a substantial proportion of total nitrogen (panels g and h of Figure 4).

Long-term, smoothed suspended solids (SS) concentrations were relatively stable or slowly declining from 1975 until approximately 1990 and have declined continuously since the early 1990s, although the rate of decline has been relatively slow since approximately 2000 (Figure 4i). The overall long-term, smoothed SS load pattern was similar to the

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Environ. Sci. Technol. 2015, 49, 3392−3400

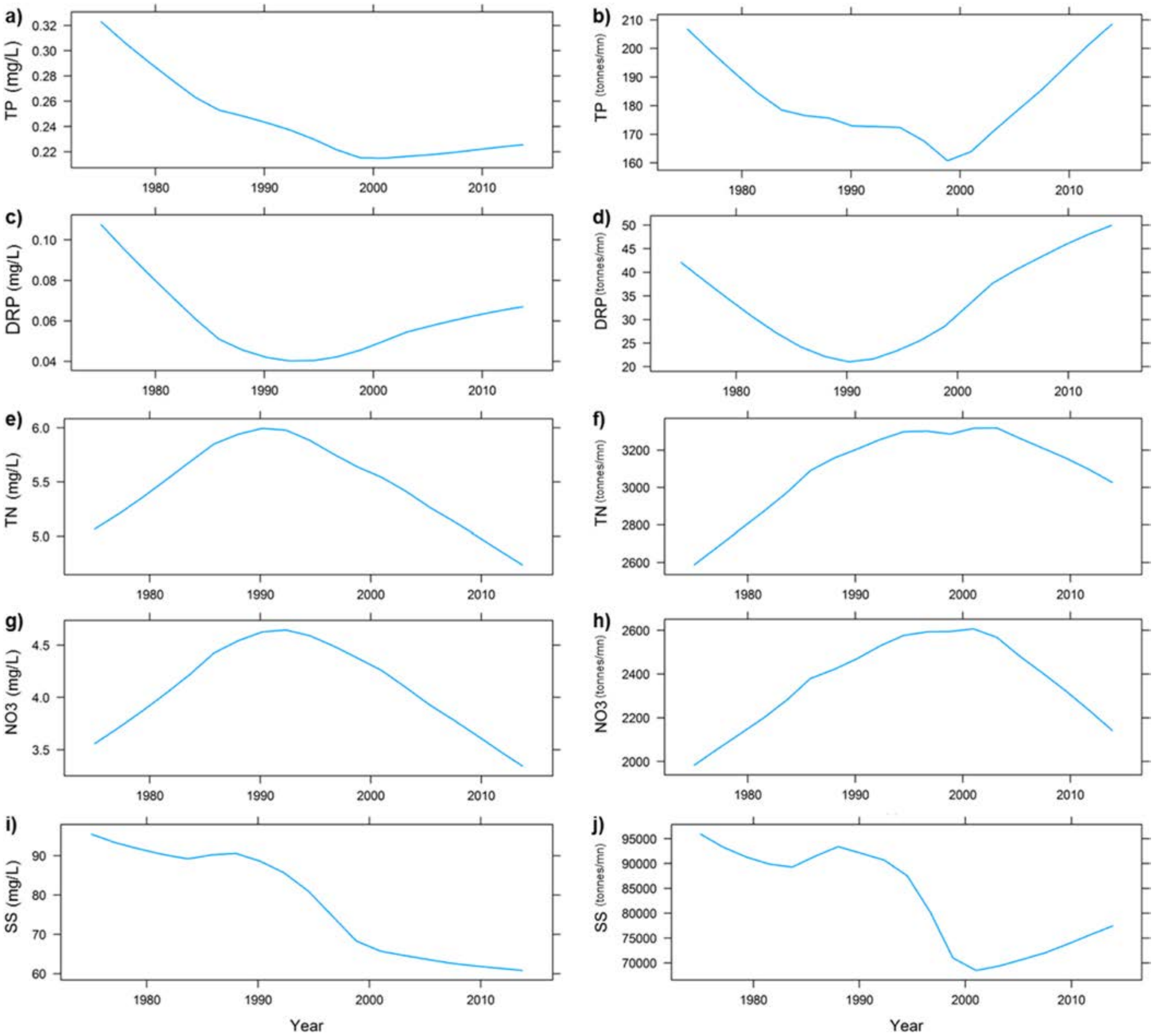

Figure 4. STL long-term trend lines (blue) for monthly average Maumee River constituent concentrations (left panels) and corresponding monthly average loads (right panels).

concentration pattern, except that the load has increased slightly since 2000 (Figure 4j).

Phosphorus, nitrogen, and SS all followed regular seasonal patterns, although their seasonal concentration cycles differed from one another (panels a, c, e, g, and i of Figure 5). TP concentrations were generally lowest from August to November, rising in December and remaining at relatively high levels into July (Figure 5a). DRP concentrations tended to drop earlier than TP, declining in March and remaining at seasonal lows through November (Figure 5c). TN and nitrate both followed a well-defined seasonal pattern with the lowest concentrations in August and September and high, relatively steady concentrations from December to June (panels d and e of Figure 5). SS concentrations generally peaked in March and April and dropped to seasonal lows from August to November (Figure 5f).

While these seasonal concentration patterns have been relatively stable over time, there are a few changes that, in the context of the ongoing problems in Lake Erie, are worth noting. Both TP and DRP have increased since the 1990s from approximately December to March, the period in which vegetative ground cover is minimal. During much of the rest of the year, slight decreases have occurred over this time period (panels a and c of Figure 5). The biggest observable change in the seasonal pattern of TN and nitrate concentrations was a steady decrease in July (panels e and g of Figure 5). July SS concentrations also steadily declined, while January concentrations have steadily increased and March concentrations have increased since the 1990s, approximately consistent with the patterns for TP (Figure 5i).

Constituent load seasonal patterns tracked the discharge seasonal pattern with peaks in March and minima running from roughly July to October (Figure 3d and right panels b, d, f, h, and j of 5). Notably, all loads decreased during March until ~1990 and have since increased (panels b, d, f, h, and j of Figure 5), approximately matching the March discharge

DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392−3400

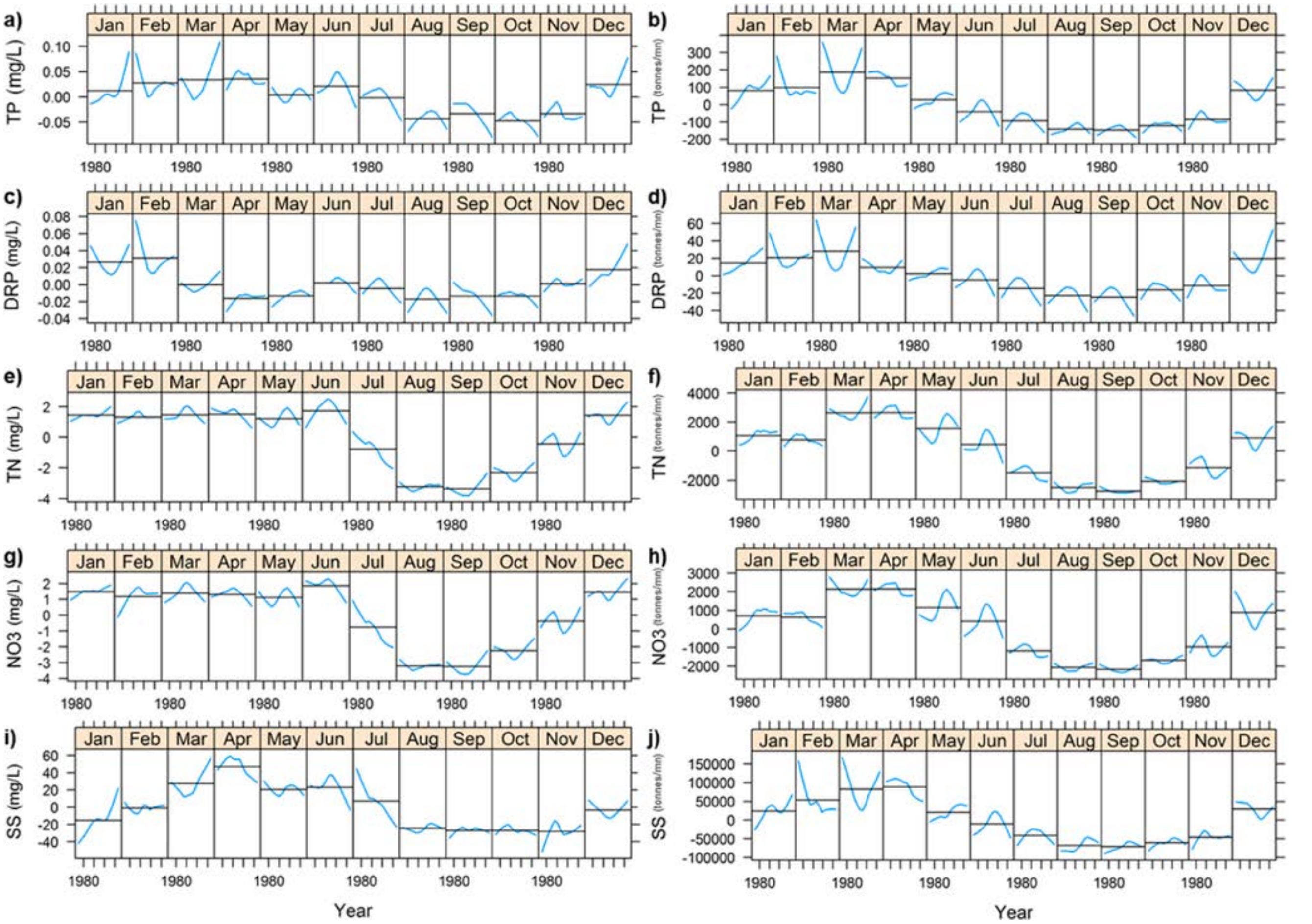

Figure 5. STL seasonal patterns (blue) and long-term monthly averages (horizontal black lines) for Maumee River constituent concentrations (left panels) and corresponding monthly average loads (right panels). Seasonal patterns are shown as deviations from the smoothed, long-term trends.

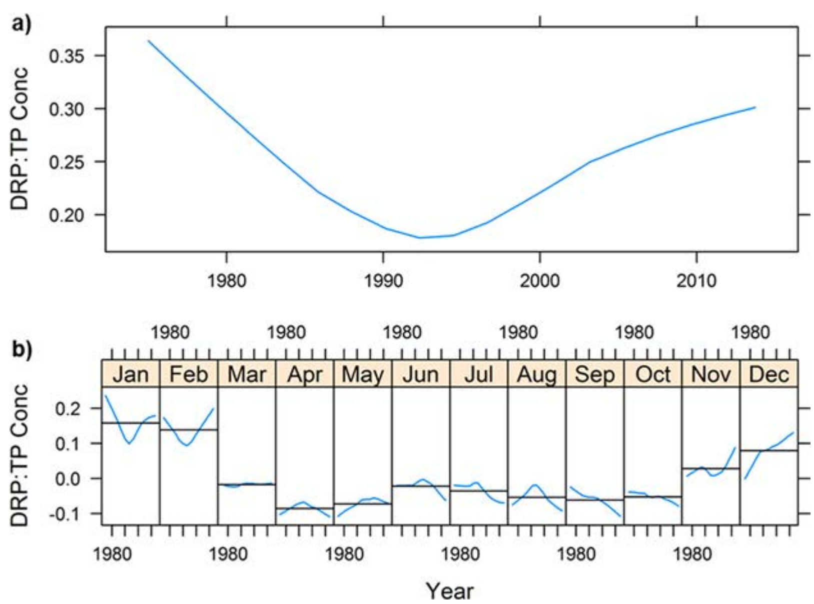

Figure 6. (a) STL smoothed, long-term trend for the DRP/TP concentration ratio and (b) STL seasonal pattern for the DRP/TP concentration ratio. Seasonal patterns are shown as a deviation from the smoothed, long-term trend.

trajectory (Figure 3d). This decline and reversal was particularly pronounced for TP, DRP, and SS, all of which also exhibit similar curves in their respective concentrations (panels a, c, and i of Figure 5).

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Environ. Sci. Technol. 2015, 49, 3392−3400

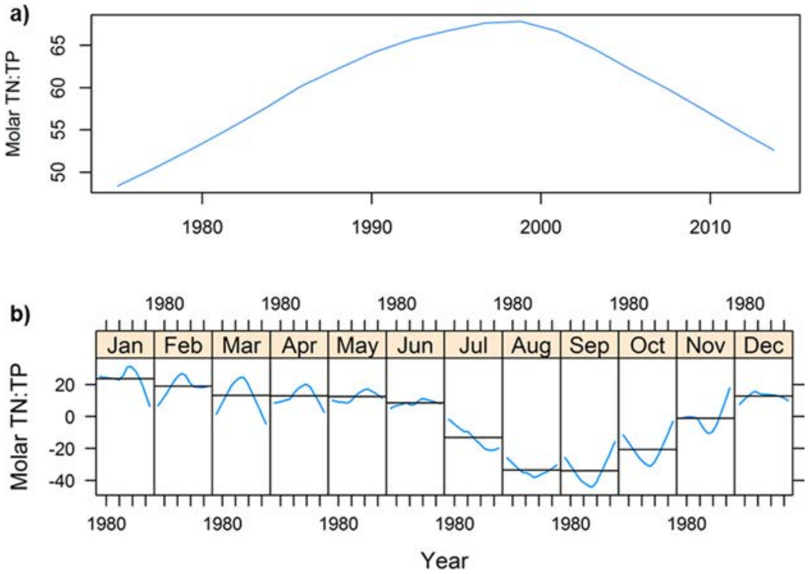

Figure 7. (a) STL smoothed, long-term trend for the molar TN/TP concentration ratio and (b) STL seasonal pattern for the molar TN/TP concentration ratio. Seasonal patterns are shown as a deviation from the smoothed, long-term trend.

In addition to changes in both concentrations and loads, we examined differences in DRP/TP and TN/TP ratios over time and seasonally (Figures 6 and 7). The long-term, smoothed DRP/TP ratio declined from 1975 through the early 1990s and subsequently increased since then (Figure 6a), similar to both the TP and DRP long-term, smoothed concentration patterns (panels a and c of Figure 4). However, the most recent DRP/TP ratio was currently somewhat below that of the beginning of the time series. Seasonally, this ratio was lowest from March to October and somewhat higher from November to February (Figure 6b). Changes over time from March to October have been minimal or more recently slightly declining, while from November to February, the ratio has been recently increasing.

The long-term, smoothed TN/TP ratio pattern was nearly the reverse of the DRP/TP pattern. The long-term, smoothed pattern increased through the late 1990s and decreased since then (Figure 7a). Seasonally, this ratio was highest from December to June and lowest from August to October (Figure 7b). In contrast to the DRP/TP ratio, the TN/TP ratio has recently been steady or slightly declining during the seasonal high period (from December to June) and increasing during the seasonal low period (from August to October) (Figure 7b).

■ DISCUSSION

Establishing the causes of recurring HABs in western Lake Erie is essential to develop effective management strategies. While it would be misleading to ascribe too much meaning to every wiggle in the long-term or seasonal STL results, a few signals seem noteworthy. Our results reaffirm previously documented concentration and load increases in the more bioavailable phosphorus fraction[13] but also indicate that discharge increases associated with increased regional precipitation are influencing loads of other important constituents. The contrasts between long-term, smoothed concentration and load patterns revealed by our results underscore the influence of a long-term discharge increase (Figure 3c) on differences in Maumee River loads. For example, smoothed, long-term TP concentrations show a slight increase since the late 1990s, whereas the smoothed, long-term TP load increase since then has been more pronounced, returning approximately to late 1970s levels (panels a and b of Figure 4). Similarly, the recent smoothed, long-term DRP load increase exceeds the corresponding concentration increase (panels d and c of Figure 4, respectively), while smoothed, long-term nitrogen concentration decreases are more pronounced than the corresponding load decreases (panels e–h of Figure 4). Concurrently, the smoothed, long-term SS concentration decrease since approximately 2000 corresponds to a load increase (panels i and j of Figure 4); in this instance, the discharge increase has more than offset the concentration decrease.

Increases in March river discharge (Figure 3d) and both TP and DRP concentrations and load (panels a–d of Figure 5) since approximately 1990 may be important factors promoting increased cyanobacterial blooms. Recent studies have suggested that phosphorus inputs from March through June are most strongly related to cyanobacterial bloom size in Lake Erie.[10,11] The observation that peak seasonal discharge (March) generally precedes peak precipitation (from approximately April to August), suggests that the March discharge is attributable to runoff from melting snowpack and high antecedent soil moisture conditions. Thus, the runoff in March probably reflects activities on the land that have occurred during the preceding winter. Investigating whether increasing phosphorus concentrations during March can be attributed to changing land-use practices during the winter months may offer clues for more effective phosphorus management.

Baker et al.[13] emphasized the importance of increasing bioavailable P inputs, and while our results confirm recent DRP increases (panels c and d of Figure 4), we also note that, during the March to June critical period, both the DRP concentrations (Figure 5c) and DRP/TP concentration ratios (Figure 6b) are at seasonal lows. These seasonal dips likely reflect the observation that SS concentrations are generally highest from March to June (Figure 5i); thus, the spring phosphorus pulse includes a relatively high proportion of particulate-associated phosphorus.

DRP load has been increasing since the early 1990s (Figure 4d) because both components of load, discharge and concentration, have been rising (Figures 3c and 4c,

DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392–3400

respectively). We suggest that both of these factors may be contributing to recent increases in HAB occurrence. Baker et al.[25] observed that storm-related discharge pulses pushed DRP further offshore than particulate phosphorus. Similarly, long-term discharge increases may be expanding phosphorus distribution over a larger portion of the lake than would occur by concentration increases alone. Higher discharge can lower hydraulic residence time and modify local circulation patterns, possibly increasing both TP and DRP delivery efficiency over a broader area. Further investigation using fine-scale hydrodynamic models may be useful to evaluate the extent to which increased discharge is influencing phosphorus availability and resultant primary productivity.[26]

Our results indicate, over approximately the same period that phosphorus has been increasing, nitrogen has been decreasing (panels e–h of Figure 4). Thus, the TN/TP ratio has also been decreasing (Figure 7a). Reavie et al.[27] reported a decline in the N/P ratio in the western and central basins of Lake Erie, possibly reflecting this trend in the river. The TN/TP ratio is lowest during the summer (Figure 7b) and may underlie reported summer nitrogen limitation in portions of the western Lake Erie basin,[28−30] although the overall decline has probably not been sufficient, thus far, to effect changes in the dominant phytoplankton species or a shift to nitrogen limitation. We note that the early 1990s onset of the long-term nitrogen decline is approximately coincident with nitrogen drops reported in rivers in the eastern United States, which have been attributed to reduced atmospheric nitrogen deposition, resulting from various emission control programs.[31] From our results, the cause of the decline cannot be ascertained. Because previous studies have implicated changing agricultural practices[13,32] as the main cause of the observed phosphorus increase, it seems plausible that regional changes in agriculture might also be responsible for the simultaneous nitrogen decline. However, the possibility that larger scale processes may also be influencing the observed nitrogen patterns invites further exploration.

Declining nitrogen inputs may also influence the toxicity of blooms in Lake Erie; recent studies have highlighted a positive relationship between nitrogen and microcystin production.[33,34] The influence of the changing ratio of phosphorus and nitrogen on the relative toxicity of *Microcystis* in western Lake Erie may also be important. Davis et al.[35] reported that toxic *Microcystis* strains have a greater need for both nitrogen and phosphorus than non-toxic strains and that toxic strains are preferentially stimulated by inorganic forms of both nutrients. The effect of concurrent phosphorus increases and nitrogen declines is unclear but merits additional research.

The 1978 GLWQA established the use of annual target loads as an accounting procedure to evaluate the effectiveness of actions taken to reduce nutrient pollution. This approach has been widely adopted under the United States Clean Water Act for a range of pollutants under the total maximum daily load (TMDL) program. While it is generally acknowledged that targets may be exceeded during years of unusually high precipitation and tributary discharge, the use of load targets remains a common management tool. However, Milly et al.[36] highlighted the growing recognition that, for variables such as tributary discharge, the assumption of stationarity, in an era of uncertain climate change, poses management challenges. Our results, indicating progressive precipitation and discharge increases in the Maumee River basin (Figure 3) and concurrent phosphorus input increases to Lake Erie (panels a–d of Figure 4), suggest that imposing fixed load targets may require phosphorus concentrations to be persistently lowered to compensate for increasing discharge, if the targets are to be achieved. As phosphorus load targets are re-evaluated pursuant to the updated 2012 GLWQA, it may be appropriate to address the possibility that continued discharge increases into the future may affect target attainment even if phosphorus reduction strategies are successful. Establishing phosphorus "substance objectives" (concentration targets) as required by the 2012 GLWQA[37] may be useful to complement load targets as a means to evaluate the effectiveness of phosphorus reduction management actions in the watershed.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Monthly time series of the Maumee River constituent concentrations and loads (Figure S1). This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported, in part, by a grant from the Great Lakes Restoration Initiative (GLERL contribution number 1746). Cathy Darnell provided assistance with graphics.

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DOI: 10.1021/es5062648
Environ. Sci. Technol. 2015, 49, 3392−3400